FINAL TECHNICAL REPORT

- AWARD NUMBER: 01HQAG0020

- RECIPIENT: Regents of the University of California

- PRINCIPAL INVESTIGATOR: Barbara Romanowicz

- TITLE: Operation of the joint earthquake notification system in Northern California: Collaboration between UC Berkeley and the USGS Menlo Park

- PROGRAM ELEMENTS: I & II

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TITLE: OPERATION OF THE JOINT EARTHQUAKE NOTIFICATION SYSTEM IN
NORTHERN CALIFORNIA:
COLLABORATION BETWEEN UC BERKELEY
AND THE USGS MENLO PARK

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PROGRAM ELEMENTS: I & II

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1. TECHNICAL ABSTRACT

In northern California, the BSL and the USGS Menlo Park collaborate to provide the timely and reliable earthquake information to the federal, state, and local governments, to public and private agencies, and to the general public. This joint earthquake notification system provides enhanced earthquake monitoring by building on the strengths of the Northern California Seismic Network (NCSN), operated by the USGS Menlo Park, and the Berkeley Digital Seismic Network (BDSN), operated by the UC Berkeley Seismological Laboratory.

During this reporting period, the BSL worked with the USGS Menlo Park to enhance and improve earthquake reporting in northern California. Important areas of activity include:

- Implementation of finite-fault estimation modules

- Improvements in moment tensor codes

- Installation and operation of ShakeMap

- Design and preliminary implementation of new software system

2. CURRENT CAPABILITIES

In 1996, the BSL and USGS began collaboration on a joint notification system for northern and central California earthquakes. The current system merges the programs in Menlo Park and Berkeley into a single earthquake notification system, combining data from the NCSN and the BDSN. Today, the BSL and USGS system forms the Northern California Management Center (NCMC) of the California Integrated Seismic Network (CISN), which is the California "region" of the ANSS.

The details of the Northern California processing system and the REDI project have been described in past reports. In this section, we will describe how the Northern California Management Center fits within the CISN system, detail developments over the time period of this grant, and discuss plans for the future development.

Figure 1 illustrates the NCMC as part of the the CISN communications ring. The NCMC is a distributed center, with elements in Berkeley and Menlo Park. The 35 mile separation between these two centers is in sharp contrast to the Southern California Management Center, where the USGS Pasadena is located across the street from the Caltech Seismological Laboratory. With funding from the State of California, the CISN partners have established a dedicated T1 communications link, with the capability of falling back to the Internet. In addition to the CISN ring, the BSL and the USGS Menlo Park have a second dedicated communication link to provide bandwidth for shipping waveform data and other information between their processing systems.

Figure 2 provides more detail on the current system at the NCMC. At present, two Earthworm-Earlybird systems in Menlo Park feed two "standard" REDI processing systems at UC Berkeley [*Gee et al.*, 2003]. One of these systems is the production or paging system; the other is set up as a hot backup. The second system is frequently used to test new software developments before migrating them to the production environment. The Earthworm-Earlybird-REDI systems perform the standard detection, location, estimation of M_d, M_L, and M_w, as well as processing of ground motion data. The computation of ShakeMaps [*Wald et al.*, 1999] is also performed on two systems, one in Menlo Park and one in Berkeley, as described above. An additional system performs finite-fault processing and the computation of higher level ShakeMaps (ShakeMaps that account for finite faulting).

The dense network and Earthworm-Earlybird processing environment of the NCSN provides rapid and accurate earthquake locations, low magnitude detection thresholds, and first-motion mechanisms for smaller quakes. The high dynamic range data loggers, digital telemetry, and broadband and strong-motion sensors of the combined BDSN/NCSN and REDI analysis software provide reliable magnitude determination, moment tensor estimation, peak ground motions, and source rupture characteristics. Robust preliminary hypocenters are available about 25 seconds after the origin time, while preliminary coda magnitudes follow within 2-4 minutes. Estimates of local magnitude are generally available 30-120 seconds later, and other parameters, such as the peak ground acceleration and moment magnitude, follow within 1-4 minutes (Figure 3).

Earthquake information from the joint notification system is distributed by pager/cellphone, e-mail, and the WWW. The first two mechanisms "push" the information to recipients, while the current Web interface requires interested parties to actively seek the information. Consequently, paging and, to a lesser extent, e-mail are the preferred methods for emergency response notification. The *recenteqs* site has enjoyed enormous popularity since its introduction and provides a valuable resource for information whose bandwidth exceeds the limits of wireless systems and for access to information which is useful not only in the seconds immediately after an earthquake, but in the following hours and days as well.

3. 2001-2004 DEVELOPMENTS

Here we recap some of the important developments in the REDI system during the contract period.

CISN Northern California Management Center
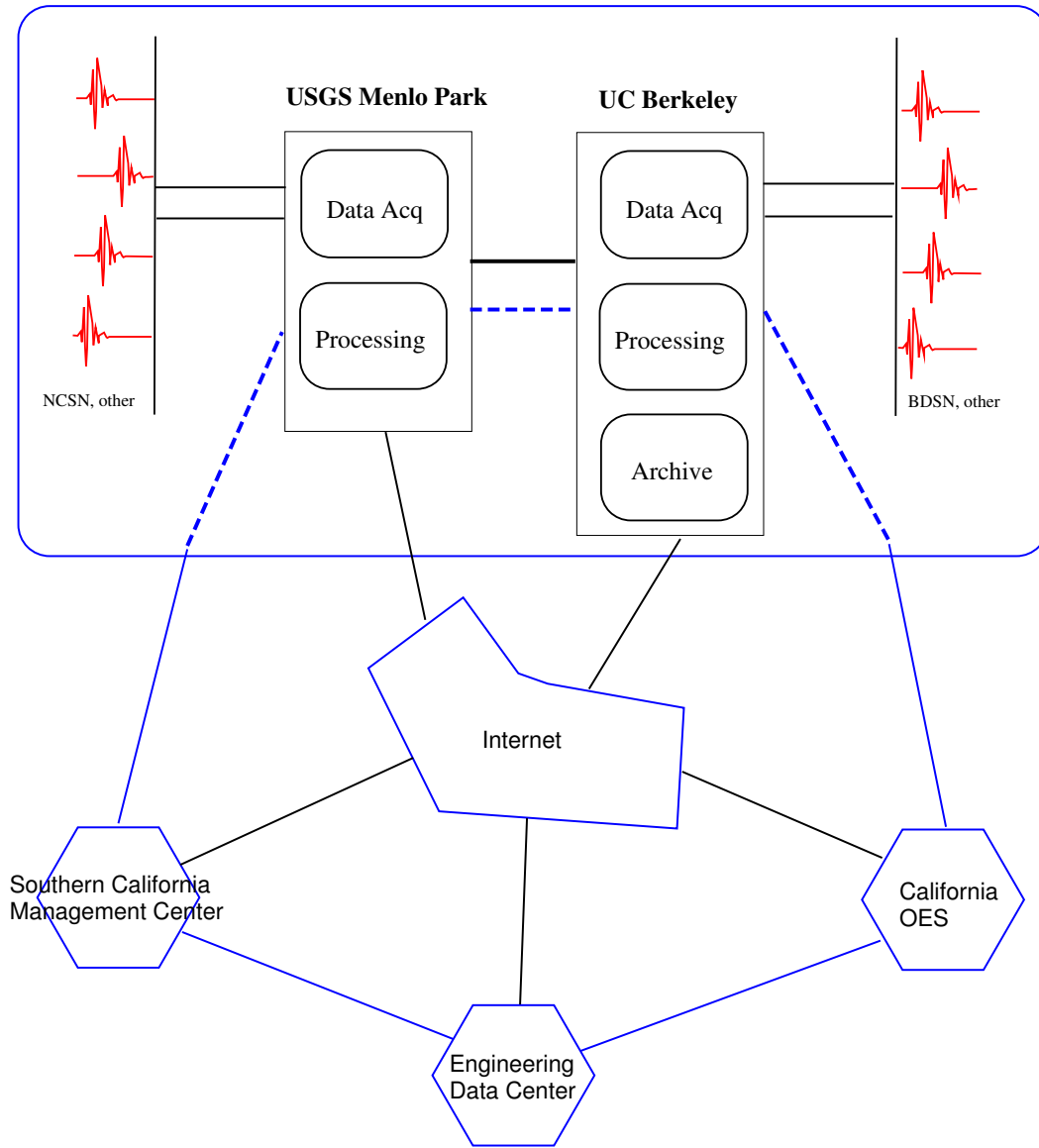
CISN Communications Ring

Figure 1: Schematic diagram illustrating the connectivity between the real-time processing systems at the USGS Menlo Park and UC Berkeley, forming the northern California Management Center, and with other elements of the CISN.

3.1 Finite Fault Estimation

At the beginning of this contract period, the BSL had started to transfer the codes for estimating faulting parameters and simulating ground motions from a development platform to the REDI operational environment. Based on the development efforts *Dreger and Kaverina* [1999; 2000], these codes use broadband waveform data combined with an estimate of the seismic moment tensor

Northern California Management Center
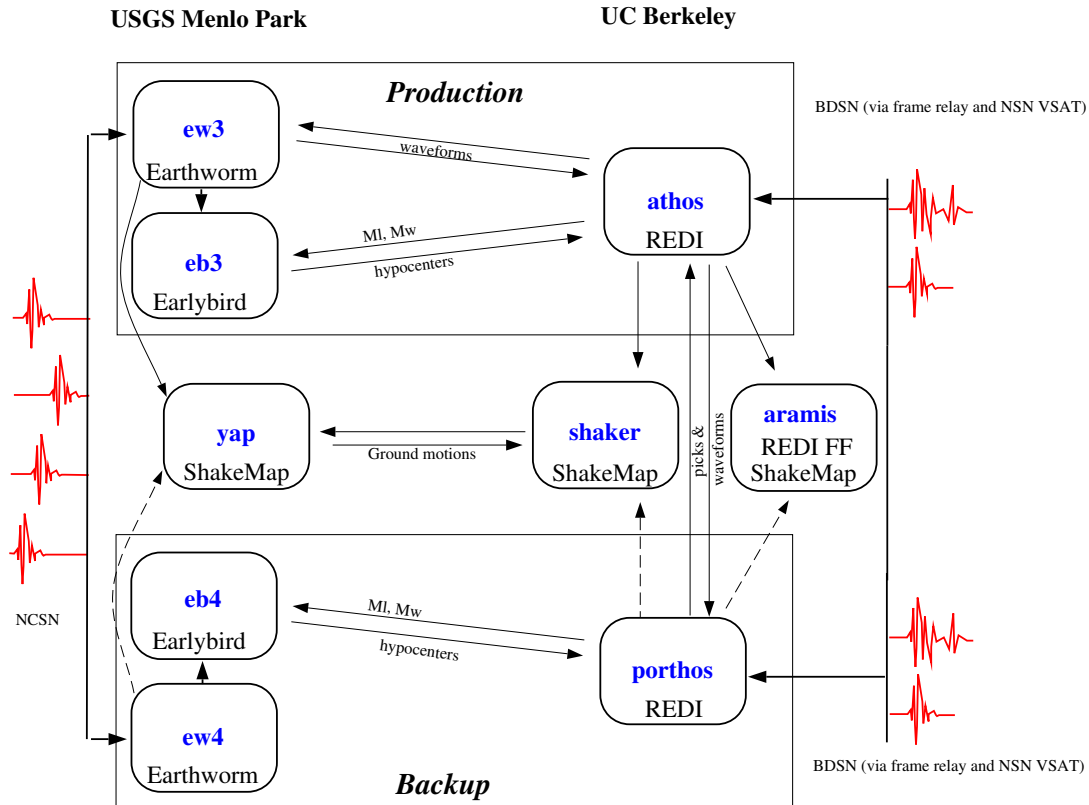
Current Implementation

Figure 2: Detailed view of the current Northern California processing system, showing the two Earthworm-Earlybird-REDI systems, the two ShakeMap systems, and the finite-fault system.

to determine faulting parameters.

At the time of this development, the "standard" REDI processing system [*Gee et al.*, 1996] was implemented within a single computer, running on each of the two data acquisition systems (athos and porthos in Figure 2). Because of the computational load of the finite-fault processing, we decided to implement these modules on a separate computer system. In order to support this effort, two additional stages were added to the standard processing (Figure 4). Stage 4 extracts the waveform data required for the finite-fault processing and Stage 5 "packs" the event up by creating a tarfile and shipping it to the finite-fault processing computer using FTP. The approach of creating a tarfile and using FTP insured a reliable data transfer since the REDI system was not using a DBMS at that time.

The second computer system (aramis in Figure 2) is running a REDI system comprised of 4 stages - two associated with the determination of finite-fault parameters and two associated with the prediction of ground motion parameters, based on the finite-fault information.

In Stage 0, waveform data are prepared for inversion and rough estimates of the fault dimensions are derived using the empirical scaling relationships of *Wells and Coppersmith* [1994]. Using these parameters to constrain the overall dimensions of the extended source, the stage tests the two possible fault planes obtained from the moment tensor inversion over a range of rupture velocities by
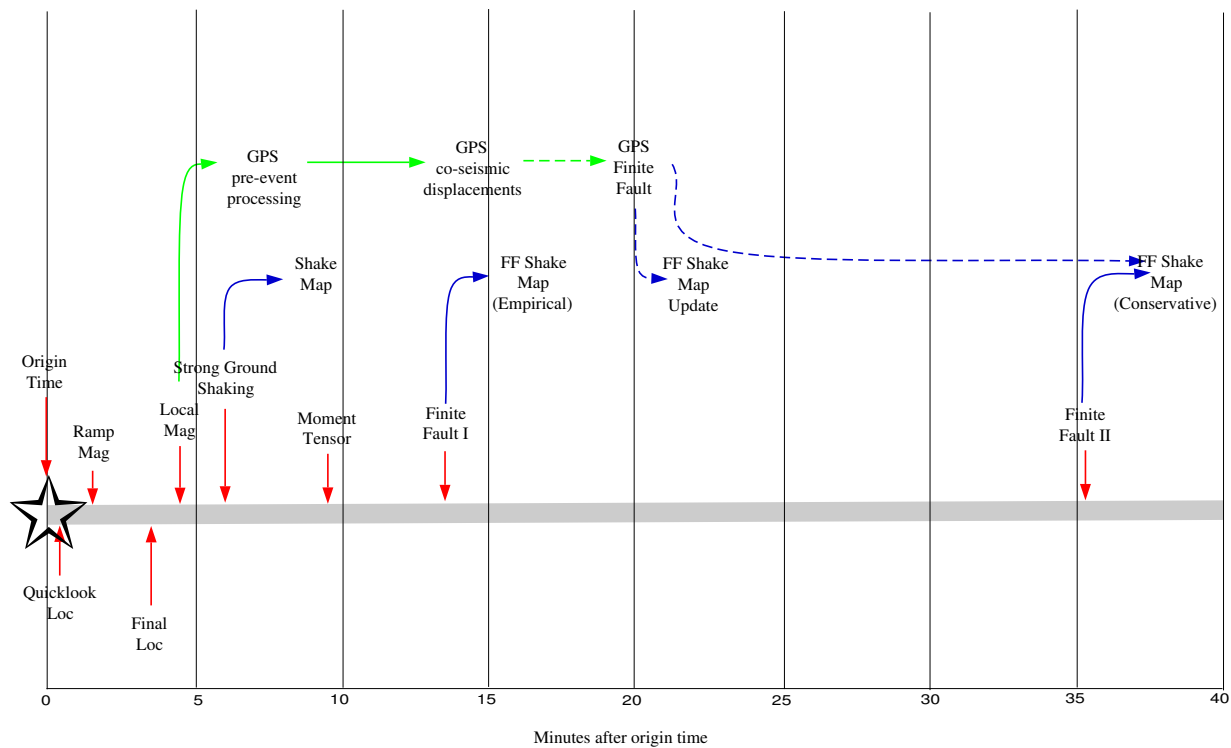
Figure 3: Illustration of the current (solid lines) and planned/proposed (dotted lines) development of real-time processing in northern California. The Finite Fault I and II are fully implemented within the REDI system at UC Berkeley and are integrated with ShakeMap. The resulting maps are still being evaluated and are not currently available to the public.

performing a series of inversions using a line-source representation. In addition to the identification of the fault plane and apparent rupture velocity, this stage yields preliminary estimates of the rupture length, dislocation rise time, and the distribution of slip in one dimension.

Stage 1 combines the results of the line-source inversion with the directivity-corrected attenuation relationships of *Somerville et al* [1997] to simulate ground motions in the near-source region. "FFShake" computes peak ground acceleration, peak ground velocity, and spectral response at 0.3, 1.0, and 3.0 sec period, which are the values used in ShakeMap, for a grid of pseudo-stations in the vicinity of the epicenter. The predicted ground motions are automatically incorporated in ShakeMap updates as described below.

In Stage 2, the second component of the finite-fault parameterization uses the best-fitting fault plane and rupture velocity from Stage 0 to obtain a more refined image of the fault slip through a full two-dimensional inversion. If line-source inversion fails to identify the probable fault (due to insufficient separation in variance reduction), the full inversion is computed for both fault planes. In the present implementation, the full inversion requires 20-30 minutes per plane, depending on the resolution, on a Sun UltraSPARC1/200e.

Stage 3 completes the cycle by simulating the near-fault strong ground motion parameters by convolving the velocity structure response with the finite-fault slip distribution. As in Stage 1, "FFShake" computes peak ground acceleration, peak ground velocity, and spectral response at 0.3, 1.0, and 3.0 sec period for a grid of pseudo-stations in the vicinity of the epicenter and pushes these ground motions to the ShakeMap system.

"Standard" REDI Processing — Multi-Stage Event Processing Queue

REDI Event Scheduler/Notifier

Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
All selected events	M ≥ 3.0	M ≥ 3.5	M ≥ 3.5	M ≥ 5.5	M ≥ 5.5
Location String Relocation (BDSN)	Revised Magnitude Ml	Peak Ground Motions Duration of Shaking (Spectral Accel *)	Moment Tensor Moment Mag Mw	Extract waveform data for Finite Fault	Package event for Finite Fault

Stage 0:
1. Pager, Email, (QDDS)

Stage 1:
1. Pager, Email, QDDS
2. Ml to EBird
3. Ml file to MP/DBMS
4. Event.txt to ShakeMap

Stage 2:
1. Pager, Email
2. GM file to MP
3. Event.txt to ShakeMap

Stage 3:
1. Pager, Email, QDDS
2. Event.txt to ShakeMap
3. Mw file to MP/DBMS, EBird

Stage 5:
1. Tar file to FF machine.

(Event tar file)

Finite-Fault REDI Processing — Multi-Stage Event Processing Queue

REDI Event Scheduler/Notifier

Stage 0	Stage 1	Stage 2	Stage 3
M ≥ 5.5	M ≥ 5.5	M ≥ 5.5	M ≥ 5.5
Finite Fault Line Source	FFShake	Finite Fault 2d model	FFShake

Stage 0:
1. (Pager, Email)

Stage 1:
1. (Pager, Email)
2. Estimates.xml & Event.txt to ShakeMap

Stage 2:
1. (Pager, Email)

Stage 3:
1. (Pager, Email)
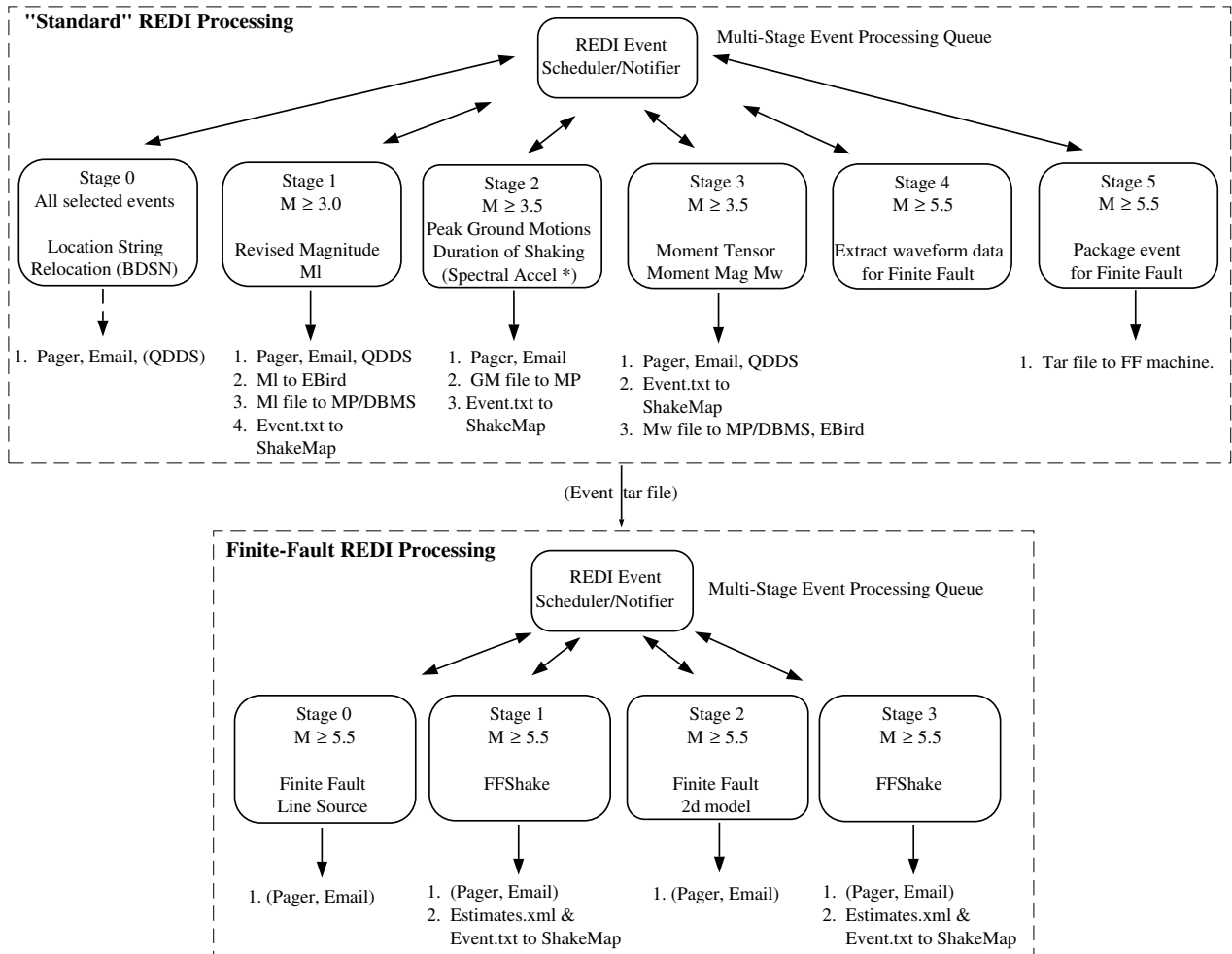2. Estimates.xml & Event.txt to ShakeMap

Figure 4: Diagram showing the two levels of REDI processing. The "Standard" processing is conducted on the two main data acquisition systems and includes the computation of M_L, ground-motion processing, and the determination of the seismic moment tensor. The "Finite-fault" system is the expansion of REDI processing. Items in parentheses are planned expansions.

The first "test" of the system was the 8/10/2001 Portola earthquake, although the event was essentially too small (M_L 5.5) to be diagnostic. However, the 12/22/2003 M_w 6.5 San Simeon earthquake provided a real test and illustrated the importance of this methodology for the rapid enhancement of ShakeMaps in areas without seismic stations.

3.2 ShakeMap

In 2001, the BSL worked with the USGS Menlo Park to install ShakeMap at UC Berkeley. Although USGS personnel had done most of the work to adapt the program to northern California, development was required to integrate the ShakeMap package into the REDI environment. In the process, BSL staff identified and fixed some minor bugs in the software.

The initial motivation for this effort was the desire to integrate the ground motions predicted from the finite-fault inversions into the ShakeMap generation. The goal is to provide updated ShakeMaps as more information about the earthquake source is available. The ShakeMap software

is structured to allow the use of different "estimates" files, that is, to incorporate ground motions predicted by alternate means.

As shown in Figure 4, the REDI processing system is integrated with the ShakeMap software at several levels. "Event.txt" files are generated at several stages - these files tell the ShakeMap software to wake-up and process an event. A ShakeMap is generated following Stage 2 in the Standard processing and updated if a revised estimate of magnitude is obtained following Stage 3.

For events which trigger the Finite-Fault processing, estimates of ground motions based on the results of the line-source computation and the full 2D inversion are produced in the "FFShake" stages. "Estimates.xml" files are generated and pushed to the ShakeMap package. The output of the line source computation produces what we call an "Empirical ShakeMap", while output from the 2D inversion produces a "Conservative ShakeMap". Figure 5 illustrates the three different methodologies with examples from an M6 earthquake which occurred in the Mammoth Lakes region in May 1999. Very few data were available to constrain these maps. This event is somewhat small for this methodology, but the impact of the successive improvements in the ground motion estimates is clearly illustrated.

Following this initial implementation in 2001 to integrate the results of ground motion simulations in ShakeMap, the BSL and USGS/Menlo Park staff met in August 2002 to discuss how to improve the robustness of ShakeMap operation in northern California. At that time, the "official" ShakeMaps in northern California depended on the operation of a single computer, located in Menlo Park. This was in contrast to other earthquake monitoring operations, where 2 parallel systems provide back-up capability should a computer fail. The BSL and USGS Menlo Park agreed to bring up a second ShakeMap system at UC Berkeley as a twin or clone of the Menlo Park system.

The implementation of the second ShakeMap system was completed in early 2003, using one of the new CISN processing computers. Both ShakeMap systems are be driven off the "production" monitoring system and both are configured to allow distribution of ShakeMaps to the Web and to recipients such as OES. At any one time, however, only one system distributes information.

In parallel, Pete Lombard at the BSL was trained to review ShakeMaps following an earthquake. Since early in 2003, the BSL and the USGS have been trading the responsibility of ShakeMap production every two weeks. The key to making a ShakeMap machine take over the production duty is to copy the earthquake database file from the former production machine to the new production machine. In that way, both machines can produce consistent ShakeMap archive lists.

The BSL has started work on a system to help with review of ShakeMaps. By modifying the program `grind`, we now write logs of the PGA and PGV values from station data, the regression curve, and the limits used by `grind` to flag outlier stations. This data is then plotted on amplitude vs. distance log-log plots. While this simple plot loses the spatial information available from a map view, it accurately reflects the process that grind uses for flagging stations. And the outlying data are more apparent on the x-y plots. For now, our plotting is done by a crude script running `gnuplot`. We intend at least to change this to use GMT for plotting. And we imagine that some day a pair of "clickable" plots could be presented on an internal Web server for use by ShakeMap reviewers.

3.3 Reliable hypocenter transfer

The USGS and BSL modified their system in 2001 to implement a reliable transfer mechanism for sending hypocenters from the Earlybird system to REDI. In 1996, the hypocenter transfer was implemented using a socket-based connection: Earlybird would open a socket, transfer the file, and then close the socket. This mechanism did not have queuing capability and events were occasionally lost during problems with connectivity between Berkeley and Menlo Park. In order to improve the reliability of the data transfers, the USGS and BSL modified their systems to use the Menlo Park "file flinger", which uses a queuing mechanism. The REDI system has used the file-flinger to send ground-motion data to the Earthworm DBMS for the last few years.
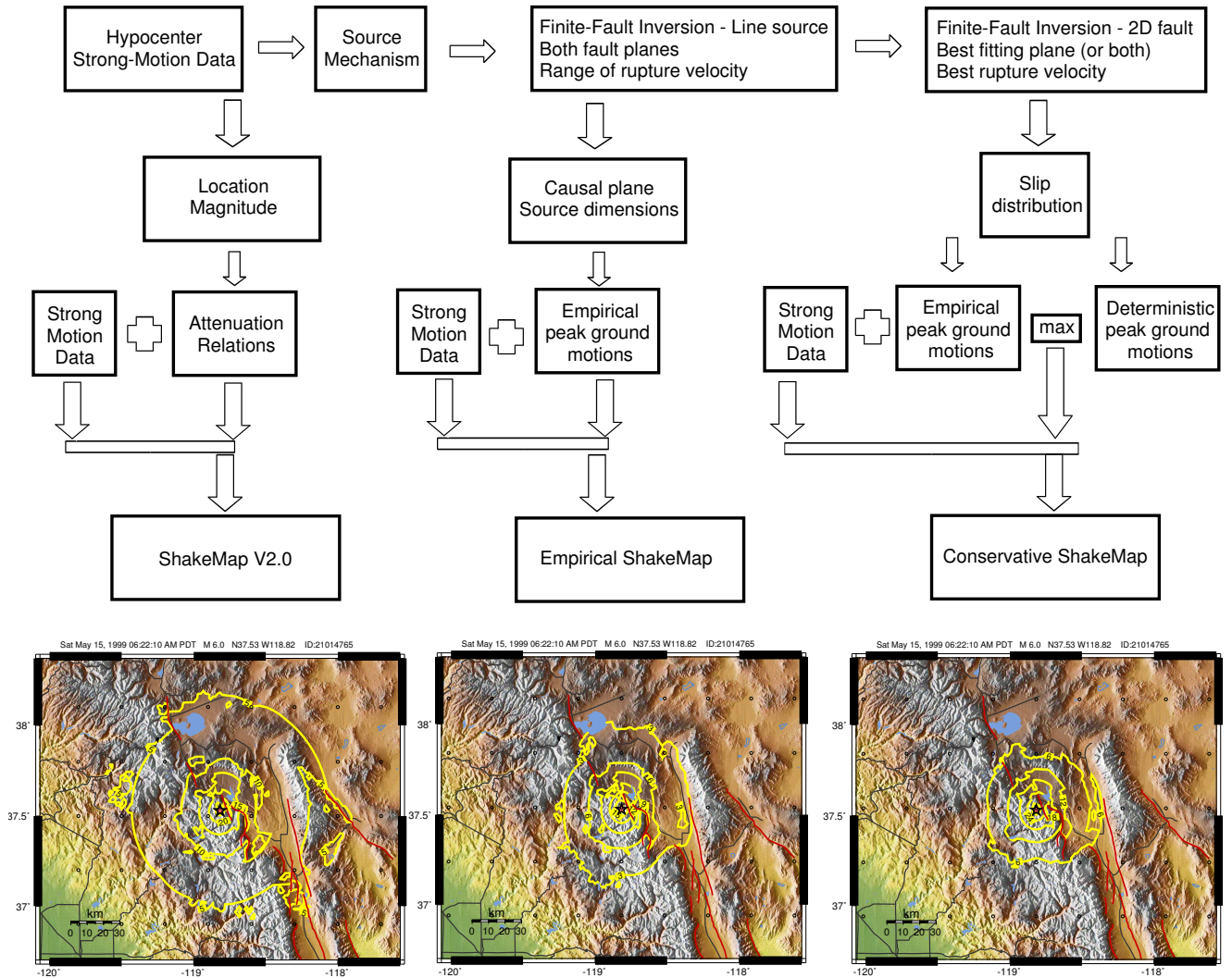
Figure 5: Summary of the three levels of ShakeMaps produced by the REDI system, with an example for an M6 earthquake in the Mammoth Lakes region. Note that the contour intervals vary from plot to plot.

3.4   Support for SNCL

In 2002, we completed the implementation of full SEED channel names in the REDI software. In the past, the REDI system had used Station/Network/Channel (SNC) to describe a unique waveform channel. However, the evolution of the BDSN and expanded data exchange with other networks created the need to implement Location code or the full SNCL convention. In parallel, the NCSN has adopted the use of the SNCL convention, as it has provided "tie-breaking" capability in describing instrumentation at a site. To support the full SEED convention within REDI, a number of modules which handle waveform data and channel-specific information required changes.

In 2003-2004, we worked with the USGS Menlo Park to implement location codes in the Earthworm software package. Northern California has been interested in using location codes for a number of years and reached an agreement with the Earthworm development team to allow Berke-

ley and Menlo Park to modify the codes. With both these code changes, the NCMC is finalizing a plan for migrating to use of these codes in real-time.

3.5   Channel selection

Most of the REDI processing modules depend on raw waveform data. An important implementation within REDI in 2002 has been a "station-availability" file which modules read before requesting data. In practice, this file is used to remove stations with telemetry problems, sensor failure, or other difficulties from processing. Concurrent with the implementation of SEED SNLC, we extended the use of this file to the channel level. Individual channels may now be controlled for use in each REDI module. For example, a channel may be used for M_L estimation, but deemed too noisy for a moment tensor inversion. Similarly, this file also allows preferences to be set among multiple channels at a particular station. For example, the moment tensor and finite-fault codes normally use data from the broadband sensors, but will select data from the accelerometers if the broadband data are clipped.

3.6   Moment Tensor codes

As part of the changes for supporting SNCL, BSL staff put considerable time into recasting the moment tensor stage of REDI. For the last 5-6 years, the REDI moment tensor stage has run two methodologies for computing moment tensors. Both of these programs were developed at the BSL as part of the research environment and then migrated to REDI operations.

The original codes are a combination of scripts and programs in C and Fortran. Many parameters such as channel usage (for example, use of LHZ, LHN, and LHE) and sampling rates were hardwired. As part of this effort, we identified several problems to be addressed: rejection of clipped data, use of an instrument response API, use of the new channel selection files, support for SNCL, and generally get away from hardwired assumptions about data rates and channel orientation. In addition, we wanted to install a new velocity model for earthquakes in the Cape Mendocino area, developed by Fumiko Tajima and Doug Dreger.

After reviewing both the complete waveform and surface wave inversion codes, the BSL decided to focus on modifications to the complete waveform methodology. These programs are more self-contained that the surface wave codes and the original developer (Doug Dreger) is still at UC Berkeley. The modifications were completed in mid-May 2002. As part of the CISN efforts to standardize and calibrate software, the complete waveform codes were packaged together along with documentation and provided to the Caltech/USGS Pasadena. BSL staff are working with Caltech personnel as they implement the moment tensor codes in southern California.

In parallel, we also developed the tools to distribute the reviewed moment tensor solutions as *recenteqs* addons.

3.7 M_w

The REDI system has routinely produced automatic estimates of moment magnitude (M_w) for many years. However, these estimates have not routinely used as the "official" magnitude, due in part to questions about the reliability of the automatic solutions. However, in response to the 05/14/2002 Gilroy earthquake (M_w 4.9, M_L 5.1) and the complications created by the publication of multiple magnitudes, the BSL and USGS Menlo Park have agreed to use automatically determined moment magnitudes, when available, to supplement estimates of local magnitude (M_L). This work was completed in the last year and M_w is now routinely reported when the solution is "good enough".

When is a solution "good enough"? This question has been under review in the last year - both to ensure reliable reporting of M_w in northern California and as part of the CISN-effort to establish rules for a magnitude hierarchy. Figures 6 & 7 illustrate a dataset compiled since the most recent modification of the moment tensor software. The dataset indicates that the estimate M_w from the complete waveform inversion is quite robust for when a variance reduction of 40% or higher is
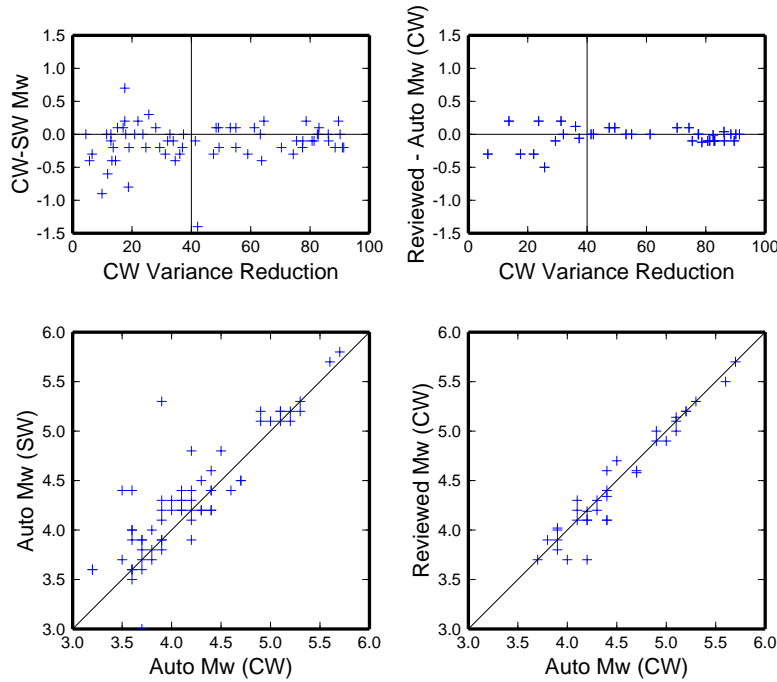
Figure 6: Left: Left: Comparison of the two regional estimates of moment magnitude – the complete waveform (CW) and the surface wave (SW) methods – from the last year of REDI results and a few older events rerun through the system. As observed in *Pasyanos et al.* [1996], the estimates of moment from the surface wave inversion are larger than the complete waveform inversion. Right: Comparison of the estimates of M_w from automatic and reviewed complete waveform solutions.

obtained. In general, earthquakes of M4.5 and higher almost always achieve that level of variance reduction. Under the current rules, the Northern California Management Center always reports M_w if the variance reduction is 40% or better.

We have also looked at comparisons between our regional estimate of M_w and the moment magnitudes determined by Harvard as part of the Centroid Moment Tensor project. Figure 8 illustrates the regional M_w compared with the CMT M_w, along with comparisons between the NEIC estimates of M_w, m_b, M_s and the CMT M_w. This dataset spans approximately 60 events in the western US and good agreement between the regional and global methods is observed, although there appears to be a systematic difference in the estimates of approximately 0.08 - 0.09 magnitude units, with the CMT estimate being higher.

3.8 Version Numbers/Quake Data Delivery System (QDDS)

In 2002-2003, the BSL and the USGS Menlo Park completed the software modifications necessary to track version numbers in the processing system. Version numbers are important for identifying the latest (and therefore hopefully the best) hypocenter and magnitude for an earthquake. Because both Menlo Park and Berkeley can be a source of earthquake information, it was critical to design a common versioning system. The modifications enabled the BSL to begin contributing solutions to QDDS, increasing the robustness of data distribution in northern California. At the present time, the USGS Menlo Park distributes solutions to 2 of the 3 QDDS hubs and the BSL distributes solutions to 2 of the 3 hubs (that is, 2 hubs receive notices from either the USGS or the BSL and 1 hub receives notices from both). This implementation should allow information to be distributed in the case of Internet shutdown of the Department of Interior (as occurred in December 2001 - see below).
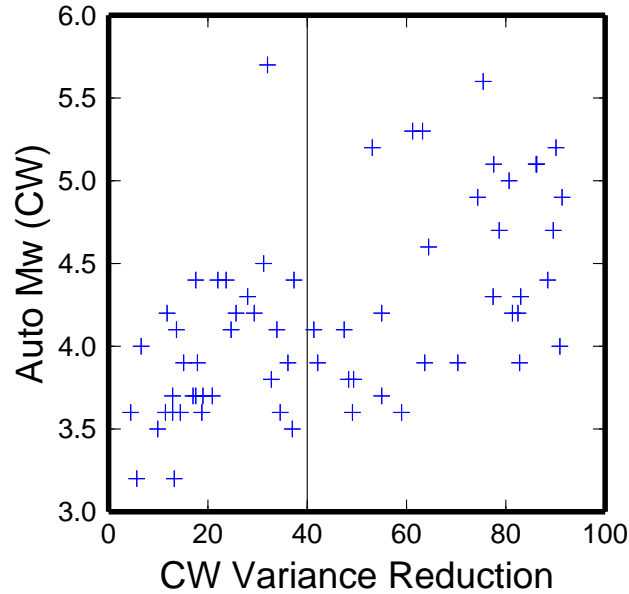
Figure 7: Results from the last year of complete waveform moment tensor inversions in the REDI system, with a few older events. With one exception, all events of M4.5 and higher achieved a variance reduction of 40%; approximately one third of the smaller events achieved the same level.

3.9 Data exchange

Over the last three years, we have worked with the University of Nevada, Reno, to enhance the earthquake monitoring capabilities in northern California and Nevada. As part of this agreement, we agreed to exchange waveform data. At the present, three-component data from BK stations CMB, WDC, MOD, and ORV and vertical component data from YBH, JCC, HOPS, WENL, SAO, and KCC are being sent to UNR. In exchange, the BSL is receiving three-component data from NN stations BEK, OMM, PAH, and WCN. In addition, UNR is forwarding data from the NSN stations WVOR, MNV, DAC, and ELK. The UNR sensors are Guralp 40Ts and these stations will enhance the REDI capabilities in eastern California and western Nevada.

We initially established this waveform exchange using the Earthworm import/export mechanisms, but experienced problems with unexplained timeouts and loss of socket connections. While BSL and UNR staff were working to resolve these problems with the Earthworm modules, IRIS negotiated a license with BRTT that allowed member universities to use components of the Antelope software system. Since UNR is using the Antelope software to drive their real-time earthquake processing system, BSL staff installed the appropriate components at UCB. The real-time waveform exchange has been migrated to the Antelope system and we are experiencing fewer problems with the exchange. This has been relatively stable for the last several months. As part of this effort, we also modified our data exchange with UCSD to use the Antelope client.

This waveform exchange is a critical first step to improving the monitoring efforts at both UNR and UCB/USGS. David Oppenheimer and Lind Gee visited the UNR Seismological Laboratory following the August 10, 2001 Portola earthquake to discuss other measures for improving earthquake monitoring in eastern California and western Nevada. As part of these discussions, work is underway to establish an exchange of parametric data as well as to provide UNR with access to the strong-motion data from the NSMP.
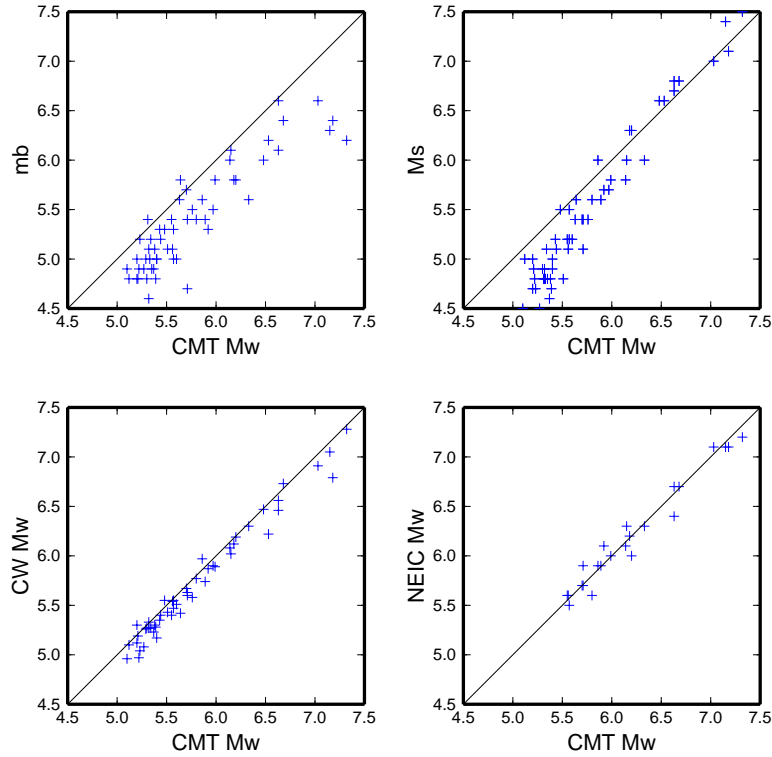
Figure 8: Comparison of several magnitudes with the M_w estimates determined from the Harvard Centroid Moment Tensor project. Lower left: Regional M_w from the reviewed solutions of the BSL; lower right: Global M_w from NEIC; upper left: m_b from NEIC; upper right: M_s from NEIC.

3.10 Database Implementation

During the past year, the BSL completed modifications to implement a database within real-time system. At this point, the database is used as a storage system, supplementing the flat files that have been the basis of the REDI system. The modified software has now been installed on both REDI platforms and is operating well.

This is the first step toward the migration of the real-time environment from the flat files currently in use in northern California to a database centric model and provides the key to better integration of the Berkeley and Menlo Park operations as well as a more seamless operation between real time and the archive. Our efforts to design and develop this system are described in the next section. Users can access the database results through a searchable interfaces at the the Northern California Earthquake Data Center: `http://quake.geo.berkeley.edu/db/Search/PI/dbselect.html`

3.11 System Development

As part of ongoing efforts to improve the monitoring systems in northern California, the BSL and the USGS Menlo Park have begun to plan for the next generation of the northern California joint notification system.

Figure 2 illustrates the current organization of the two systems. As described above, an Earthworm/Earlybird component is tied to a REDI component and the pair form a single "joint notification system". Although this approach has functioned reasonably well over the last 8 years, there are a number of potential problems associated with the separation of critical system elements by 30 miles of San Francisco Bay.

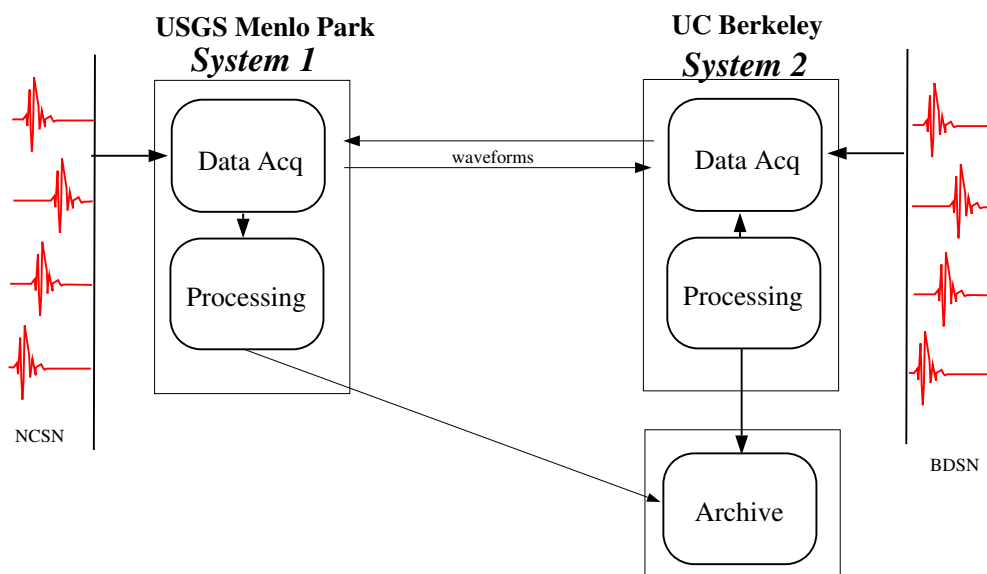# Northern California Earthquake Notification System

Future

Figure 9: Future design of the Northern California Earthquake Notification System. In contrast with the current situation (Figure 2), the system is being redesigned to integrate the Earthworm/Earlybird/REDI software into a single package. Parallel systems will be run at the Berkeley and Menlo Park facilities of the Northern California Operations Center.

Recognizing this, we intend to redesign the Northern California operations so that a single independent system operates at the USGS and at UC Berkeley. Figure 9 illustrates the overall configuration. In FY01/02, our discussions proceeded to the stage of establishing specifications and determining the details required for design. In FY02/03, however, most of the development effort focused on CISN activities and specific plans for the "next generation" Northern California system were put on hold. This enforced wait provided the opportunity for some ideas to mature and the current plans for the NCMC are somewhat different from those envisioned in 2001.

The current design draws strongly on the experience in Southern California for the development of TriNet (Figure 11), with some modifications to allow for local differences (such as very different forms of data acquisition). In addition, the BSL and the USGS want to minimize use of proprietary software in the system. The TriNet software uses three forms of proprietary software: Talerian Smart Sockets (TSS) for inter-module communication via a "publish and subscribe" method; RogueWave software for database communication, and Oracle as the database management system. As part of the development of the Northern California Earthquake Data Center, the USGS and BSL have worked extensively with Oracle databases and extending this to the real-time system is not viewed as a major issue. However, we did take the opportunity to review options for replacing Smart Sockets and RogueWave with Southern California, resulting in joint agreement on replacement packages and shared development effort.

In the last year, BSL staff, particularly Pete Lombard, have become extremely familiar with portions of the TriNet software. We have begun to adapt the software for Northern California, making adjustments and modifications along the way. For example, Pete Lombard has adapted the TriNet magnitude module to northern California, where it is running on a test system. Pete

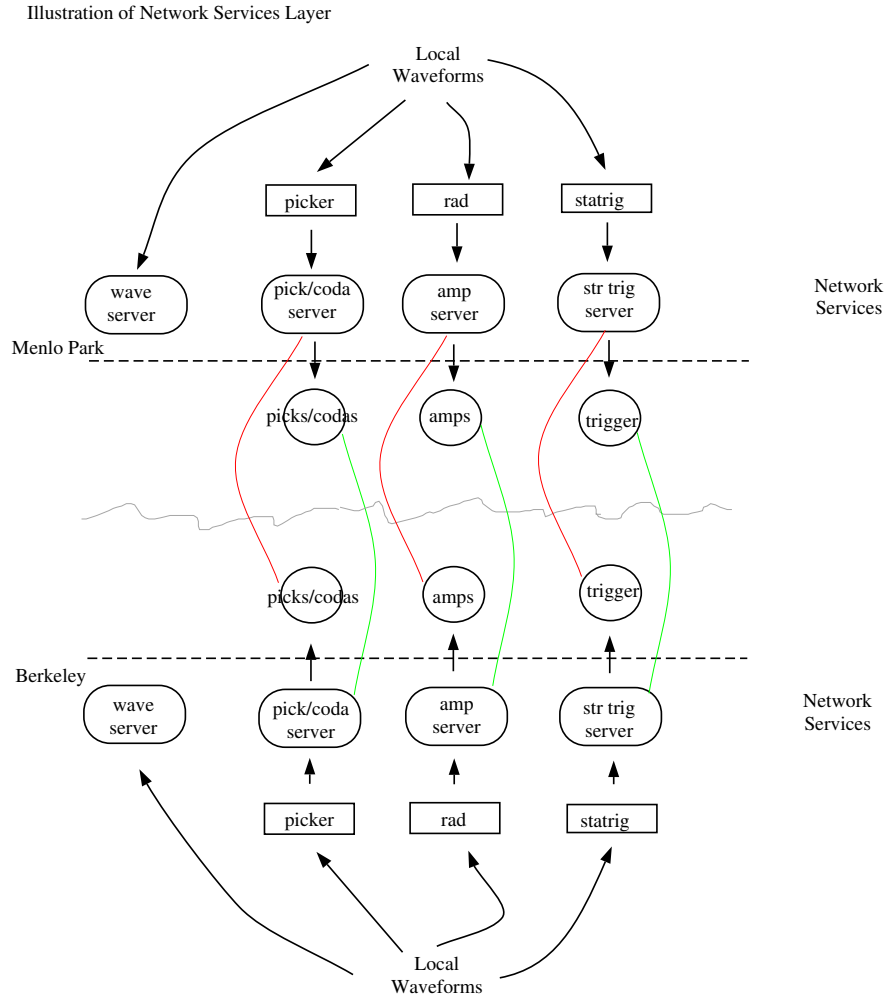Illustration of Network Services Layer

Figure 10: Illustration of the network services layer envisioned as part of the Northern California system, showing the picks/codas, amplitudes, triggers, and waveform services that will form the base of the parallel monitoring systems.

made a number of suggestions on how to improve the performance of the magnitude module and has worked closely with Caltech and the USGS/Pasadena on modifications. One of the recent discoveries with the magnitude module was related to differences in the use of time bases in the database schema between northern and southern California.

More recently, the BSL and the USGS Menlo Park undertook the effort to develop and test a design to exchange "reduced amplitude timeseries". One of the important innovations of the TriNet software development was the concept of continuous processing [*Kanamori et al.*, 1999], where waveform data are processed to produce Wood Anderson synthetic amplitudes and peak ground motions constantly. The system produces a reduced timeseries, sampled every 5 secs, that modules can access to retrieve amplitudes in memory (stored in an "Amplitude Data Area" or ADA) to calculate magnitude and ShakeMaps as needed. In the the past year, the BSL and the USGS Menlo Park have collaborated to establish the tools for the ADA-based exchange. As part of the software development in northern California, several modules have been developed:

The first, ada2ring, reads from an ADA, creates an EW message, and plops it into a ring where it can be picked up and transferred between computers using the standard EW import/export. The second, ring2ada, will take the EW amplitude message and put it into the ADA. More recently,
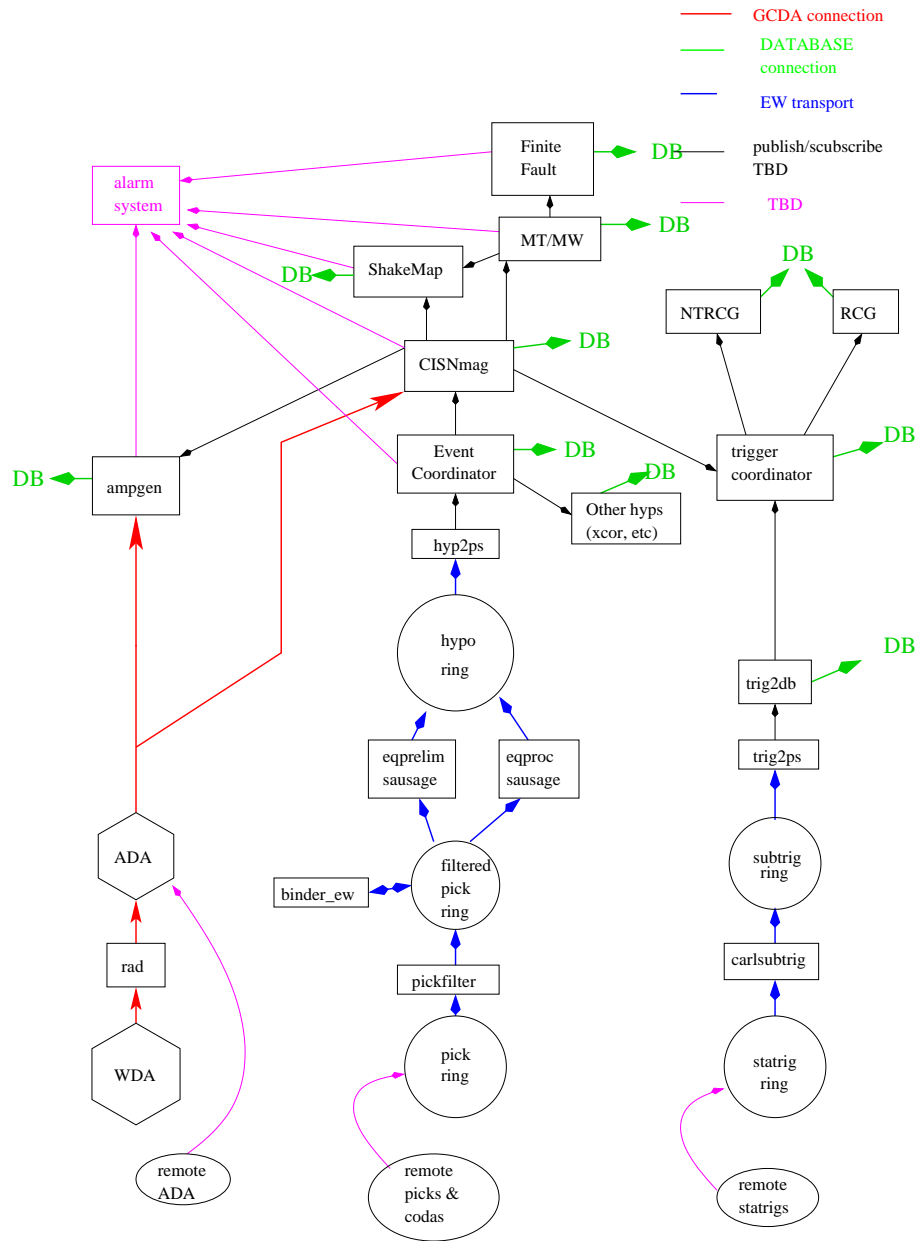
Figure 11: Illustration of the modules that will be part of the monitoring system in northern California, showing communication between modules and the database. This plan draws upon Earthworm modules for picking, triggering, association, and location; TriNet modules for magnitude, amplitude generation, and coordination between events and triggers; REDI modules for moment tensor and finite fault processing; and ShakeMap.

some development in northern California now allows multiple rads to work on the same time base and feed a single ADA (solving the problem of multiple rads working on the same channels).

This system is currently being tested in northern California, with ADAs in Menlo Park and Berkeley feeding an ADA in Berkeley that is being used to test the magnitude codes.

Additional capability needed in the future includes the capability to filter channels in the ADA (so that NoCal does not send CI timeseries back to SoCal, for example), and the ability to handle location codes (currently in the NC version but not in the SC version).

More information on the Northern California software development efforts is available at `http://www.cisn.org/ncmc/`.

4.   2001-2004 EARTHQUAKE MONITORING

During the time period of this contract, over 30,000 events were processed by the joint notification system in northern California. Most of these events were small earthquakes, although a number represent mislocated teleseisms, microwave glitches, or other blown events. Of the total, 1223 events had an M_d greater than 3.0, 339 events had an M_L greater than 3.5, and 8 earthquakes with M_L greater than 5 was recorded, including the December 22, 2003 San Simeon earthquake.

Below we describe some of the interesting events - earthquakes and others - that occurred during this time period, emphasizing, where appropriate, the lessons learned.

4.1   2001 Portola earthquake

On August 10, 2001 at 20:19:26UTC a M_L 5.5 event occurred 15 km west of Portola, California (39.893, -120.638). This event was processed by the automatic system and a seismic moment tensor was obtained within 8 minutes, indicating a strike-slip mechanism (strike=328., rake=-170., dip=84) with scalar seismic moment of 4.39e+23 dyne cm. Although small, this event provided the first operational test for the finite-fault system described above.

Stage 0 yielded a rupture velocity of 1 km/s, the lowest allowed. The low value reflects the desire of the code to attempt to map slip close to the hypocenter. Although the line source results indicated a slight preference for the NW trending plane, the difference was so slight that both planes were tested during the full 2D inversion. The Stage 2 results were a variance reduction measure of goodness of fit of 10.9% for the SW-trending plane and 10.4% for the NW trending plane, indicating the difficulty with the small event.

This event occurred in eastern California, where the density of seismic stations is relatively low and highlighted the importance of collaboration with neighboring networks. Shortly after the earthquake, Lind Gee (BSL) and David Oppenheimer (USGS) spent a day in Reno, discussing topics such as waveform exchange, authoritative boundaries of rapid notification and catalog production, and after hours contact information.

4.2   2001 DOI Internet shutdown

On Thursday, Dec. 6, 2001, the USGS was ordered to disconnect all external Internet connections by the Office of the Secretary of the Interior. The order included email as well as popular Web pages and lasted for 3 days.

BSL and USGS Menlo Park staff worked feverishly on the 5th and 6th to set up mechanisms for distributing earthquake information through UC Berkeley, using the private network which connects them. For several years, the recenteqs Web pages have been available through the NCEDC (`http://quake.geo.berkeley.edu/recenteqs/`) and this site was publicized broadly so that the public would be aware of the alternative resource. In addition, the BSL set up temporary redistribution hubs for QDDS messages from northern California so that the recenteqs maps at the NCEDC and at the SCEDC would have access to the earthquake messages. A similar setup through Caltech provided access to southern California events. Thirdly, the BSL worked with the USGS so that ShakeMaps generated in Menlo Park would be hosted on the NCEDC (`http://quake.geo.berkeley.edu/shake/`). Software was set up to allow BSL staff to send out email notification of earthquakes to USGS clients; USGS paging was unaffected.

The NCEDC Web server saw a doubling of hits during the days of the DOI Internet shutdown. The recenteqs Web pages became the 3rd most popular URL at the NCEDC and the ShakeMaps were not far behind at 20th (in November 2001, the recenteqs URL did not show up on the list of top 30 URLs at the NCEDC).

4.3   2002 McCone generator failure

On March 7, 2002, a campus-wide power outage occurred when moisture seeped into a UC Berkeley electric substation. The power failed a few minutes before 5:00 PM local time. BSL staff immediately noticed that the McCone generator failed to start. Phone calls were made to Physical Plant and Campus Services (PPCS), but the extended nature of the outage prevented PPCS staff from responding for over two hours.

During this time, BSL staff made several attempts to bring the McCone generator online. The initial failure of the generator was traced to a weak battery. When BSL staff replaced the battery, the generator started up and then shut itself off after several minutes, due to a leak in the water pump.

As a result of the failure of the generator, the REDI system went off the air around 5:30 PM when the UPS system shut down due to a low battery condition (the UPS is designed to carry the electrical load until the generator comes online). A subset of critical computers were brought back online when a personal generator belonging to BSL staff. was brought in around 8:00 PM. A temporary fix to the generator was provided by PPCS around 8:30 PM, which allowed the rest of the processing system to be restored. The generator was not fully repaired until March 26th, 19 days after the power outage.

The failure of the McCone generator was due to poor maintenance. Since the 2002 power outage, the BSL has worked with PPCS to establish a routine of quarterly load tests, which should improve screening for problems such as this, as well as working with other groups to relocate the critical activities to more robust campus facilities.

A future project for the BSL and the USGS Menlo Park is to establish combined notification by paging. Currently, each institution performs paging for its own set of clients. A combined system would allow either institution to perform paging to all clients and thus take advantage of the physical separation and separate infrastructure to enhance robustness.

4.4   2002 Gilroy

On May 14, 2002, a moderate earthquake occurred on the Castro fault, just off the San Andreas, near Gilroy. The M_L 5.1 event had a M_w of 4.9. Although a small magnitude difference in the absolute, many lifelines and other agencies activate their response at magnitude 5.

The REDI system has routinely produced automatic estimates of moment magnitude (M_w) for many years. However, these estimates have not routinely used as the "official" magnitude, due in part to questions about the reliability of the automatic solutions. However, in response to the Gilroy earthquake and the complications created by the publication of multiple magnitudes, the BSL and USGS Menlo Park have agreed to use automatically determined moment magnitudes, when available, to supplement estimates of local magnitude (M_L). The debelopment effort was described above.

4.5   2002/2003 Swarms in San Ramon and Dublin

In late November 2002, a small swarm of earthquakes occurred near the Calaveras fault in San Ramon. The largest event was a M_w 3.9, with 4 events over M3.5. The pre-Thanksgiving events were felt over a large area - the Community Internet Intensity Map reports approximately 2400 responses for the M3.9. The Northern California Management Center put together an Internet report on the sequence and posted it on the CISN Web page: `http://www.cisn.org/special/evt.02.11.24/`.

In early February, a small swarm of earthquakes occurred near the Calaveras fault in Dublin. The largest event in this sequence was an M_L4.2, with 3 events of M3.5. In contrast to the events in November, these events occurred sub parallel to the Calaveras fault (Figure 12). As in November, these events were felt over a broad area, although no damage was reported. Because of the attention focused on these earthquakes and the possible implications for the Calaveras fault, the Northern California Management Center published an Internet report on the CISN Web page: `http://www.cisn.org/special/evt.03.02.02/`.
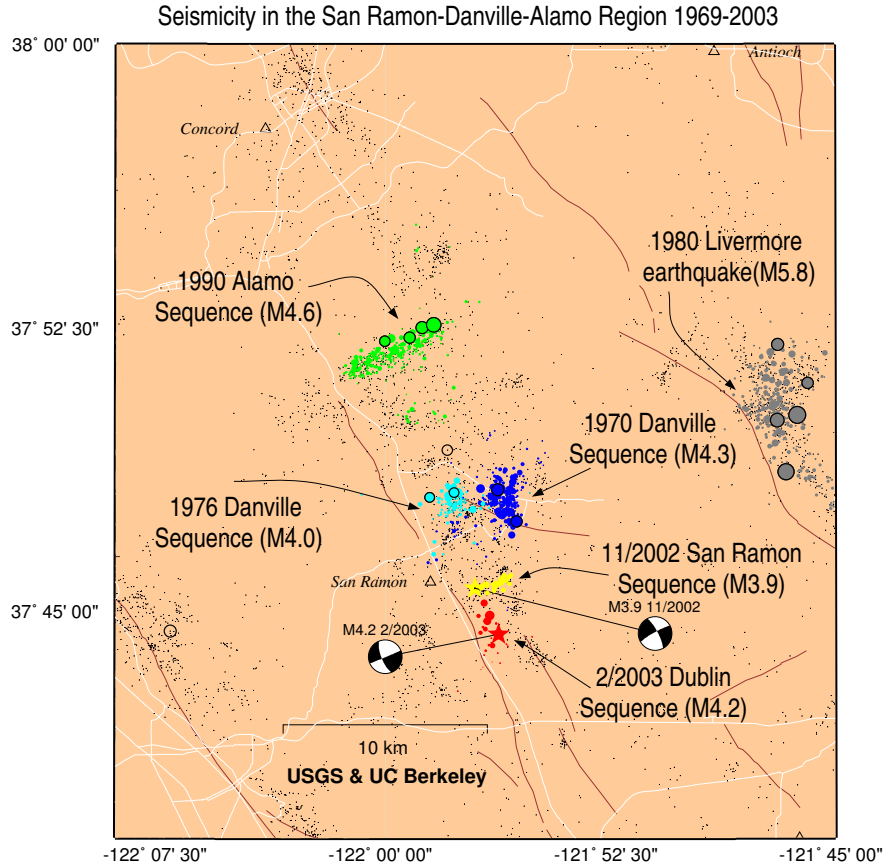
Figure 12: This map illustrates the Feb 2003 Dublin and Nov 2002 San Ramon swarms in the context of historical seismicity. Earthquakes from the USGS catalog 1970-2003 are plotted, with events of $M_L \geq 4.0$ plotted with large circles. Events associated with various sequences are plotted in color: 1970 Danville (blue), 1976 Danville (turquoise), 1980 Livermore (grey), and 1990 Alamo (green). Events from the 2002 swarm are plotted in yellow and the events from 2003 are plotted in red.

4.6   2003 San Simeon

The December 22, 2003 M6.5 San Simeon earthquake is the largest event in California since the 1999 M7.1 Hector Mine earthquake and results in 2 deaths and over 50 injuries (Figure 13). Preliminary reports suggest that the most severe damage was to unreinforced masonry structures that had not yet been retrofitted [e.g., *EERI*, 2004]. Significant damage to water tanks has also been reported and a number of wineries suffered significant loss of wine barrels and their contents. In the following description, we draw upon the San Simeon report of the CISN [*Gee et al.*, 2004].

The automated procedures of earthquake location and magnitude determination worked well (Tables 1 and 2). A preliminary location was available within 30 seconds, and a final location with a saturated duration magnitude (M_d) of 5.6 was released approximately 4 minutes after the event occurred. An updated and more reliable local magnitude (M_L) of 6.4 was released 30 seconds later, and the final moment magnitude (M_w) of 6.5 was released 6.5 minutes after the earthquake origin time. The automatically determined first motion mechanism and moment tensor solution each showed a reverse mechanism, in excellent agreement with the reviewed mechanisms.

One of the most challenging aspects of this event was the lack of ShakeMap-quality stations in the vicinity of the earthquake, particularly stations with communications capability. The closest
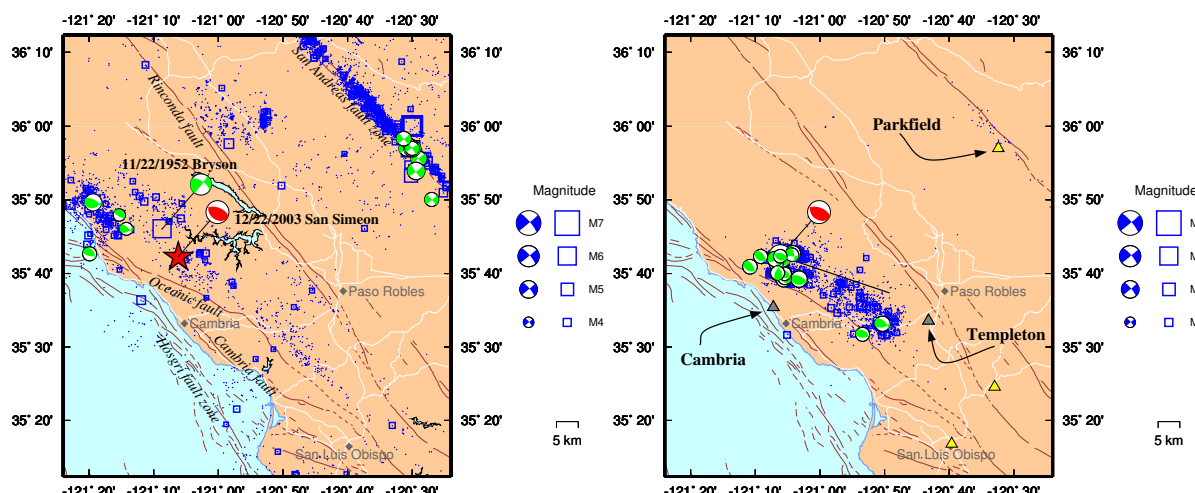
Figure 13: Left: Map showing the seismicity from 1966-2003 in the region of the San Simeon earthquake. Earthquakes with magnitude less than 3 are plotted as points; events with magnitude greater than 3 are plotted as squares. Moment tensors solutions over the last 10 years are plotted in green. The location and mechanism of the M6.5 event are shown in red. Also shown is the location and first-motion mechanisms of the 1952 Bryson earthquake [*Dehlinger and Bolt*, 1987]. Right: Earthquakes and moment tensors in the region of the San Simeon earthquake since the 12/22/03 mainshock. The aftershock region extends from the mainshock to the southeast. The solid line indicates the extent of the line source determined on the 22nd for improving the ShakeMap. Triangles indicate the location of stations used in the ShakeMap - yellow indicates near real time stations; grey indicates stations without communications that were not available in near real time. Stations mentioned in the text - Cambria, Templeton, and Parkfield - are labelled.

such station to the epicenter with continuous telemetry was the UC Berkeley station PKD, in Parkfield, CA, at a distance of 56 km. The California Geological Survey (CGS) operates three stations in the area - Cambria at 13 km, San Antonio Dam at 22 km, and Templeton at 38 km from the epicenter. However, since these stations did not have telemetry, their data were not available until hours after the earthquake. Caltech/USGS Pasadena operate stations to the south of the event, but their nearest station was 60 km from the epicenter.

The first automatic ShakeMap was posted 8 minutes after the event, based on the M_L of 6.4 and with 29 stations contributing. The first update occurred 6 minutes later based on the revised M_w of 6.5 and the addition of 45 stations (mostly distant). Throughout December 22nd and 23rd, the ShakeMap was updated multiple times with additional data (including the observations from the CGS stations at Templeton and Cambria) and as more information about the earthquake rupture (fault orientation and length) became available.

The San Simeon event provided an important proving ground for the finite fault processing. The automatic codes performed correctly, although a configuration mistake caused the inversion to use the lower quality of the two moment tensor solutions obtained. As a result, the finite-fault system did not obtain optimal results. The computations proved to be relatively fast in this implementation, with the line source inversion completed approximately eight minutes after the event occurred and the resulting predicted ground motions available six minutes later. The 2-D inversion and the predicted ground motions were completed 30 minutes after the earthquake.

Although the automated system had a configuration error, the processed data were available for rapid review by the seismic analyst. Using available strong motion and broadband displacement waveforms, both line-source and planar-source analyses indicated that this event ruptured nearly horizontally to the SE from the epicenter, essentially in the null-axis direction of the NE dipping reverse mechanism. Because of this nearly horizontal, along dip rupture, it was not possible to uniquely determine the causative fault plane, although there was a slight preference for the NE
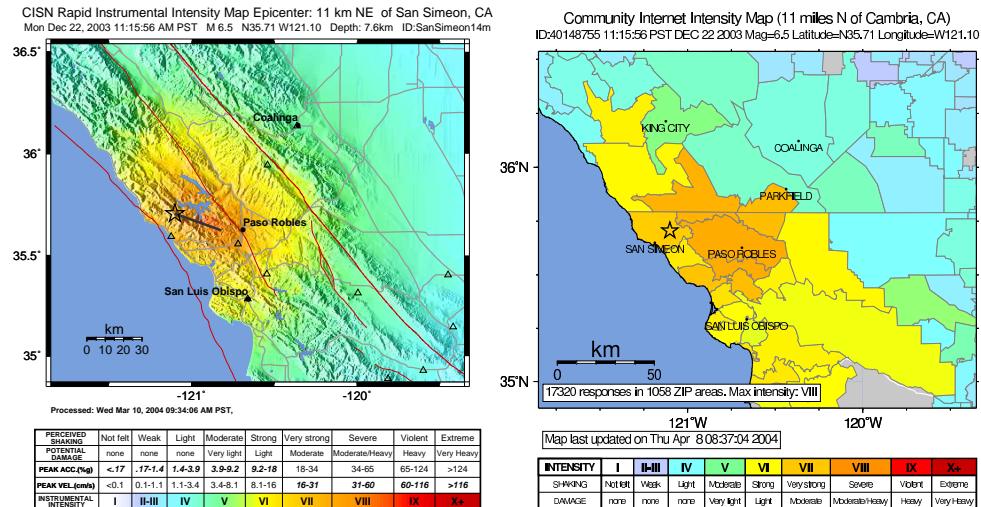
Figure 14: Left: Map of instrumental intensity for the M6.5 San Simeon earthquake, after correction for the fault distance calculation. Right: Close-up of the Community Internet Intensity Map for the San Simeon earthquake.

dipping plane which is consistent with aftershock distribution. The southeast rupture produced directivity-amplified ground motions toward the SE that is consistent with felt reports and the damage in Paso Robles. The preliminary results from the reviewed finite source analysis were included in the ShakeMap system approximately 4 hours after the earthquake.

Only a few ShakeMaps have made use of finite source information in the past - the 1999 Hector Mine and 2001 Denali earthquakes are examples. As noted earlier, the use of finite source information is not automatically included in the ShakeMaps available to the public. Because this component of the system has been seldom exercised, the San Simeon earthquake uncovered a problem in the code used to compute distances to a rupture segment. As a result, the ShakeMaps in Figure 15c-f underestimate ground motions near the middle of the fault trace. Figure 14 displays the revised intensity map, which shows a broader area of intensity VIII than observed in Figure 15f.

The lack of nearby ShakeMap-quality stations resulted in maps with an overwhelming reliance on theoretically predicted ground motions. Figure 15 illustrates the evolution of the intensity map with time. In Figure 15a and b, the source is modeled as a point source and the maps show areas of significant ground motions south and north of the epicenter. Four hours after the earthquake, information about the fault rupture was added (c), based on the inversion results of *Dreger et al.* [2004, see below]. The addition of the finite fault information (in this case, limited to the linear extent and orientation of the fault) focused the higher ground motions to the southeast and showed more damaging shaking in the vicinity of Paso Robles. However the most significant change in the ShakeMap came with the addition of data from the Templeton station, seven hours after the earthquake (d). The high shaking observed at Templeton (47% g), raised all the intensity levels significantly. Maps (e) and (f) show the intensity level after the addition of the Cambria data and the map as of January 5, 2004.

As seen in Figure 15c, the addition of information about the fault length and orientation was an important addition to the ShakeMap, particularly given the sparseness of instrumentation. This methodology provides an important tool in areas with limited station distribution to improve ShakeMaps.

CISN Timing		
Earthquake Information	UTC Time	Elapsed time (HH:MM:SS)
Origin Time (OT)	12/22 19:15:56	00:00:00
Quick Look hypocenter	12/22 19:16:20	00:00:24
Final hypocenter & M_d	12/22 19:20:25	00:04:29
Local Magnitude	12/22 19:20:58	00:05:02
First Motion mechanism	12/22 19:21:36	00:05:40
Moment Tensor mechanism & M_w	12/22 19:22:40	00:06:44
1st ShakeMap completed (M_L 6.4)	12/22 19:24:13	00:08:17
Analyst review/1st aftershock probabilty	12/22 19:32:00	00:16:04
2nd ShakeMap completed (M_w 6.5)	12/22 19:38:28	00:22:32
Analyst review of moment tensor	12/22 20:16:49	01:00:53
1st Internet Quick Report at cisn-edc.org	12/22 20:30:–	01:14:–
Analyst review of line source	12/22 21:54:–	02:38:–
ShakeMap update with line source	12/22 23:33:–	04:17:–
ShakeMap update with Templeton data	12/23 02:34:–	07:18:–
Earthquake Report at cisn.org	12/23 17:34:–	22:18:–
Updated aftershock probabilty	12/23 22:54:–	27:38:–
ShakeMap update with Cambria data	12/24 00:28:–	29:12:–
Preliminary science report at cisn.org	12/24 23:44:–	52:28:–

Table 1: Timing of earthquake information for the San Simeon earthquake.

| Parameters of the Dec 22, 2003 San Simeon Earthquake		
	Automatic	Reviewed
Origin Time (UTC)	19:15:56.24	19:15:56.20
Location (latitude longitude)	35.7058 -121.1013	35.7043 -121.1032
Depth (km)	7.59	7.34
M_d	5.62	5.35
M_L	6.43	6.44
M_w	6.50	6.50
FM Mechanism (strike/dip/rake)	297/56/97 105/35/80	305/60/71 160/35/120
MT Mechanism (strike/dip/rake)	294/59/83 128/32/102	290/58/78 131/34/108
MT Depth (km)	8.0	8.0

Table 2: Comparison of parameters as determined by the automatic earthquake processing system with those obtained after analyst review. Note that the value of M_d is lower than the M_L or M_w as the duration magnitude estimate generally saturates around M4.0-4.5. FM - first motion; MT - moment tensor.
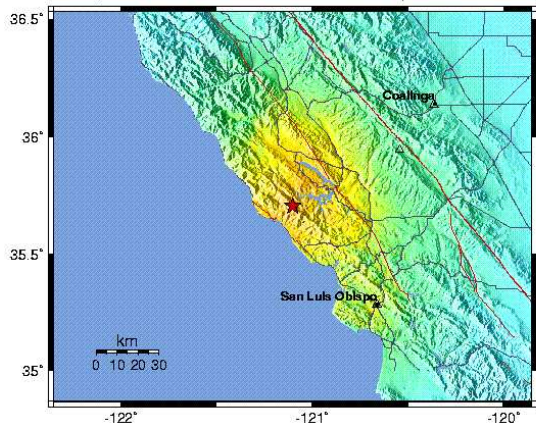
A: 12/22 11:24 AM First ShakeMap with ML 6.4.
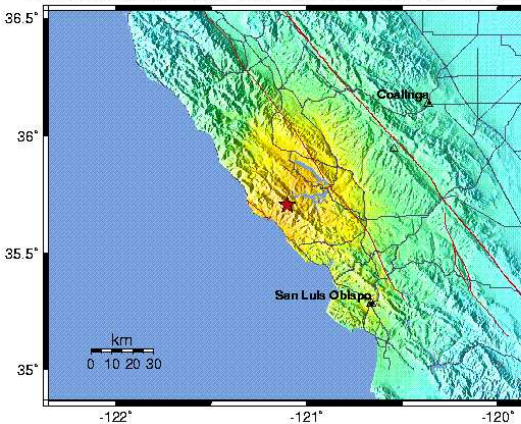
B: 12/22 11:38 Update with additional stations and Mw 6.5
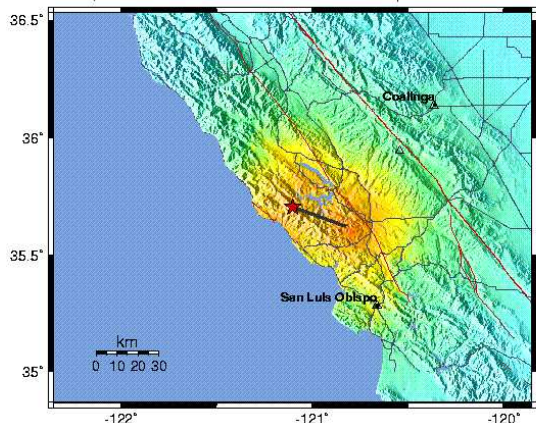
C:12/22 15:33 Update with addition of finite fault description.
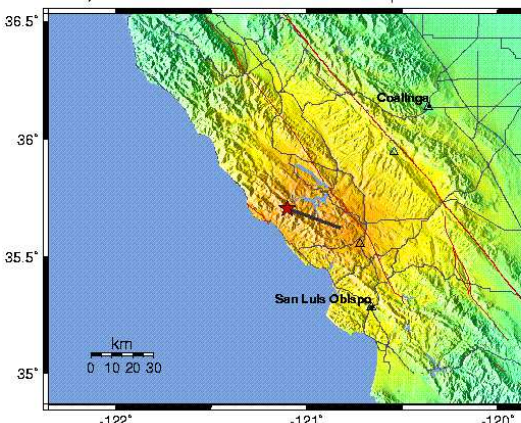
D: 12/22 18:34 Update with data from the Templeton station.
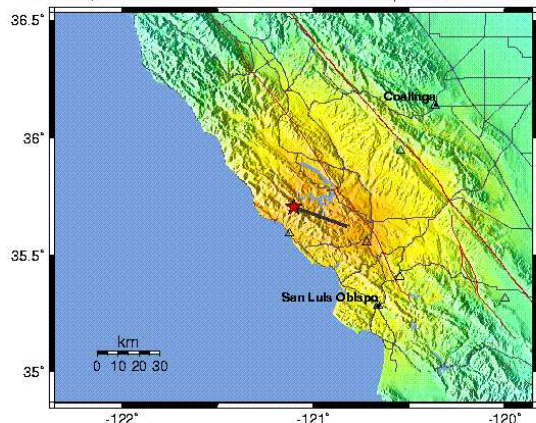
E: 12/23 16:28 Update with data from the Cambria station.
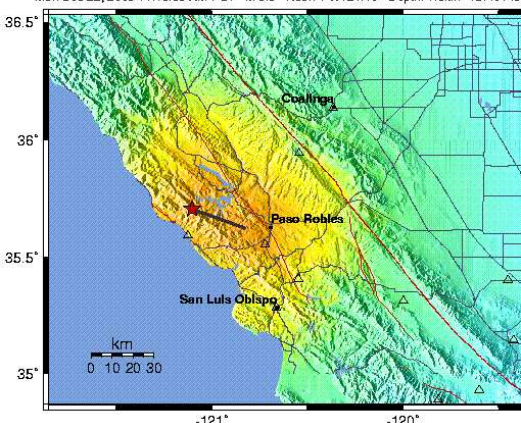
F: ShakeMap as of 1/5/2004.

Figure 15: The temporal evolution of ShakeMaps for the San Simeon earthquake, as illustrated through the intensity maps. All times are local.

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6. NON-TECHNICAL ABSTRACT

This project focuses on the development and implementation of hardware and software for the rapid assessment of earthquakes. The Berkeley Seismological Laboratory collaborates with the USGS Menlo Park to monitor earthquakes in northern California and to provide rapid notification to public and private agencies for rapid response and assessment of earthquake damage. In the past year we improved the robustness of the computation of ShakeMaps through the establishment of parallel ShakeMap system at the BSL, began to use databases in our real-time processing system, and began the design and development of software to improve the Northern California Seismic System.

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9. DATA AVAILABILITY

Data and results from the REDI project are available at the Northern California Earthquake Data Center (*//www.quake.geo.berkeley.edu*) For additional information on the REDI project, contact Lind Gee at 510-643-9449 or lind@seismo.berkeley.edu.

Annual Non-Technical Summary

AWARD NUMBER: 01HQAG0020

OPERATION OF THE JOINT EARTHQUAKE NOTIFICATION SYSTEM IN NORTHERN CALIFORNIA:
Collaboration between UC Berkeley
and the USGS, Menlo Park

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PROGRAM ELEMENTS: I & II

KEY WORDS: Seismology; Real-time earthquake information

INVESTIGATIONS UNDERTAKEN

This project focuses on the development and implementation of hardware and software for the rapid assessment of earthquakes. The Berkeley Seismological Laboratory collaborates with the USGS Menlo Park to monitor earthquakes in northern California and to provide rapid notification to public and private agencies for rapid response and assessment of earthquake damage. In the past year we improved the robustness of the computation of ShakeMaps through the establishment of parallel ShakeMap system at the BSL, began to use databases in our real-time processing system, and began the design and development of software to improve the Northern California Seismic System.